



Saskatchewan
Research Council

**SOME CLIMATOLOGICAL ASPECTS OF DUST STORMS
AND THEIR IMPACT ON SOIL EROSION IN THE
AGRICULTURAL LANDS OF SASKATCHEWAN**

by
E.E. Wheaton

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ABSTRACT

There is no clear and informative definition or classification for dust storms. This study is an attempt to redress that fact as well as to examine the conceptual models, impacts and significance of dust storms. The temporal and spatial characteristics of dust storms are and examined. Several recommendations for further study are made.

The dust storm definition developed herein is as follows:

A dust storm is an atmospheric disturbance characterized by moderate to strong winds which results in blowing dust and which, in turn, produces reduced visibility.

Definitions are provided for moderate to strong winds and reduced visibility.

The following genetic dust storm classification developed and discussed herein is as follows:

- 1) convection dust storm (air mass)
- 2) frontal dust storm (wind shift)
- 3) pressure gradient dust storm (wind storm)
- 4) mixed type dust storm

Two conceptual models of the dust storm process are provided. One is a flow chart type and makes use of the dust storm definition. The other is a more general model and it draws upon the genetic classification as well as exhibiting the relationships of the factors which determine dust availability.

Several other important 'firsts' characterize this

study. This paper is the first attempt to present the quantitative temporal distribution of dust storms for any province in Canada. It is the first attempt to map the spatial distribution of dust storms for any area, to the author's knowledge.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	i
ACKNOWLEDGEMENTS	iii
LIST OF TABLES	v
LIST OF FIGURES	v
1 INTRODUCTION	1
1.1 Dust Storm Definitions	1
1.2 Processes of Dust Storms and the Associated Wind Erosion	5
1.3 Dust Storm Classifications	14
1.4 Impacts of Dust Storms on Agriculture and the Significance of the Study	22
1.5 Study Area	24
2 STUDY OBJECTIVES	29
3 NATURE AND AVAILABILITY OF DATA AND PROCEDURE	30
3.1 Nature and Availability of Data	30
3.2 Recommended Procedures	33
4 CASE STUDIES OF DUST STORMS - THE HISTORICAL AND RECENT BACKGROUND	36
5 TEMPORAL CHARACTERISTICS OF DUST STORMS	37
6 SPATIAL CHARACTERISTICS OF WIND EROSION AND DUST STORMS	43
7 SUMMARY AND CONCLUSIONS	47
8 RECOMMENDATIONS	48
9 REFERENCES	49

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Dust Storm and Dust Whirl Definitions	2
2	Annual Frequency of Days with Blowing Dust, 1977 to 1983	27
3	Total Monthly Number of Days with Blowing Dust (D), Saskatchewan Stations	28

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Dust Storm - Wind Erosion Process, a Flow Diagram	7
2	A Basic Model of the Dust Storm - Soil Erosion Process	8
3	Variation of the Threshold Velocity with Grain Size and Specific Gravity	10
4	Wind Velocity Distributions Without (----) and With (—) Movement of Sand	11
5	The Wind Erosion Potential of Climate (Climatic Factor) Based on the 1951 to 1980 Normals . . .	23
6	Study Area (South of the Northern Administra- tive Area) and Land Use	25
7	Recording Wind Network	31
8	Areal Mean Annual Frequency of Days with Dust Storms (1977-1983), Saskatchewan	38
9	Distribution of the Mean Monthly Frequency of Dust Storms (1977-1983), Saskatchewan	39
10	Mean Annual Dust Storm Frequency, Agricultural Saskatchewan (1977-1983)	44

1 INTRODUCTION AND LITERATURE REVIEW

1.1 Dust Storm Definitions

In order to focus on a climatological analysis of dust storms, a definition is needed. Yet, no clear, generally accepted definition of dust storm as yet exists (WMO 1983). Present definitions include mention of strong winds, dust and other earth particles in the air and a reduction in visibility (Byers 1959; Navarra 1979; WMO 1983) (Table 1). Navarra (1979) also labels the dust storm as an unusual, frequently severe weather condition.

These definitions are not sufficiently clear, quantitative, or accurate. Although the dust storm may be considered severe as Navarra (1979) indicates, it is not unusual and can be considered common in arid and semiarid lands (Pewe 1981). Also, depending on the definition of strong winds, dust storms can be initiated by wind speeds of a lesser magnitude than those generally considered to be strong. In practice, the threshold velocity or critical wind velocity at which some of the grains are dislodged and set in motion by fluid pressure has a wide range of values for any soil (WMO 1983:77). Shikula (1981) also reports that the wind velocity thresholds that have been observed at the beginning of dust storms differ widely. For example, threshold wind velocities were found to vary from 3 to 20 ms^{-1} . So, although dust storms occur in conjunction with strong winds, exceptions can be found.

Table 1. Dust Storm and Dust Whirl Definitions.

Term	Definition (Source)
Dust storm or sandstorm	- an ensemble of particles of dust or sand energetically lifted to great heights by a strong and turbulent wind (Byers 1959).
Dust storm (also called Black Blizzard)	- an unusual frequently severe weather condition characterized by strong winds and dust filled air over an extensive area (Navarra 1979).
Blowing dust or blowing sand	- dust or sand raised by the wind to moderate heights above the ground. The visibility at eye level may be reduced to 5/8 of a mile (Environment Canada 1977).
Dust storm	- occurs when horizontal visibility is reduced to less than one kilometre (Banoub 1970; Goudie 1978).
Dust storm	- when prevailing station visibility is less than or equal to one kilometre (U.S. National Weather Service in Nickling and Brazel 1984).
Dust whirl	- a well developed, small scale whirlwind or dust whirl. Diameters range from 10 ft. to greater than 100 ft.; average height is about 600 ft. but few have been observed as high as several thousand feet (Cole 1980).
Dust whirl or sand whirl or dust devil	- an ensemble of particles of dust or sand, sometimes accompanied by small litter, raised from the ground in the form of a whirling column of varying height with a small diameter and an approximately vertical axis (Byers 1959).
Dust devil	- a small whirlwind common in dry regions and made visible by dust and debris picked up from the ground (Navarra 1979).

Banoub (1970) and Goudie (1978) confront the problem of subjectivity of definitions by defining a dust storm as occurring when horizontal visibility is reduced to less than 1 km. This definition is very similar to the one given by Environment Canada (1977) for blowing dust or sand (Table 1). Thus, the recording of an occurrence of blowing dust could be synonymous with a dust storm occurrence. It is considered so for the purposes of this study.

Although the definitions by Banoub (1970) and Goudie (1978) are quantitative, they omit much of the useful information that is often included in the qualitative definitions. So these can also be improved upon. Another omission common to all of the aforementioned definitions is the recognition that dust storms are a type of storm. This aspect should be stated directly rather than be inferred. Just as a storm in which thunder is heard can be broadly termed a thunderstorm (Environment Canada 1977; Blair and Fite 1965), a storm in which blowing dust occurs and restricts visibility can be termed a dust storm.

In view of the strengths and weaknesses of the existing definitions, the following draft definition of the dust storm has been developed.

A dust storm is an atmospheric disturbance characterized by moderate to strong winds which results in blowing dust and which, in turn, produces reduced visibility.

Where:

Moderate to strong winds are those winds which equal or exceed the threshold velocity at which grains are dislodged by fluid pressure (WMO 1983:77).

Reduced visibility occurs when horizontal visibility is restricted to less than or equal to one kilometre.

This definition is a more comprehensive, quantitative and accurate portrayal of the dust storm.

Since there are no definitions for dust storm onset and cessation that the author is aware of, the following definitions have been developed. The onset of the dust storm can be defined as the time at which visibility is reduced to one km or less by blowing dust. The cessation of the dust storm can be defined as the time at which the reduction in visibility due to blowing dust becomes greater than 1 km.

The dust whirl or dust devil is often discussed in association with the dust storm (Table 1). The dust whirl has much less impact on soil erosion because of its small scale, brief duration and localization. In comparison to a dust whirl, the area covered by a dust storm is vast, even exceeding a million square kilometres (WMO 1983:14). In contrast, the diameter of a whirlwind is usually less than 15 m (WMO 1983:15). The durations of the dust whirl and dust storms are also quite different. The former has a life cycle of minutes while the latter has a life cycle of hours to several days (WMO 1983:14). Also, in a temperate climate dust whirls cause very little soil deflation (WMO 1983:15), therefore are of less significance environmentally, espe-

cially for agriculture. Dust storms are larger and more persistent than the dust whirl and thus can be considered more significant especially in terms of effect. For these reasons an analysis of the dust whirl will not be included herein.

The other type of storm often referred to in association with the dust storm is the sandstorm. They can be differentiated by the size of airborne particles. Particle diameters in dust storms are less than or equal to 0.1 mm, while particle diameters in sandstorms are greater than 0.1 mm (WMO 1983:93). Both a dust storm and a sandstorm can occur simultaneously, depending mainly on the availability of different soil textures. Both storms have the same definition of visibility reduction. Since climatological records do not differentiate an occurrence of blowing dust from that of blowing sand, a sandstorm will be considered a dust storm in this study.

1.2 Processes of Dust Storms and the Associated Wind Erosion

The primary mechanism of soil erosion during a dust storm is wind erosion, although water erosion can also take place if rainfall occurs with the storm. Thus there is a strong association between dust storms and wind erosion. Blowing dust is a prerequisite of the storm being a dust storm. For these reasons the impact of dust storms by means of wind erosion rather than water erosion is the focus of

this study.

Dust storms are visible indicators of wind erosion taking place. The type of wind erosion that takes place is both intensive and extensive; it is not, for example, the weak localized type that is associated with whirlwinds. Wind erosion has been classified into these two types depending on the scale and duration of the erosion (WMO 1983: 13).

One of the more comprehensive definitions of wind erosion is provided by Wilson and Cooke (1980:217) as "the process by which loose surface material is picked up and transported by the wind, and surface material is abraded by wind-blown particles." By definition then, dust storms contain the blowing particles of wind erosion and the blowing dust type of wind erosion is the unique characteristic of a dust storm. The blowing dust differentiates dust storms from the other types of storms, just as hail or thunder differentiates hailstorms and thunderstorms.

The main factors influencing wind erosion and the resulting soil degradation are climate, soil properties, topography, fetch (unsheltered distance) and vegetation (Figures 1 and 2). The interaction of these factors is complex. Human activities strongly influence soil properties, vegetative cover and sometimes fetch in many locations. Human activity usually results in the extensive and increasing destabilization of the earth's surface thereby increasing

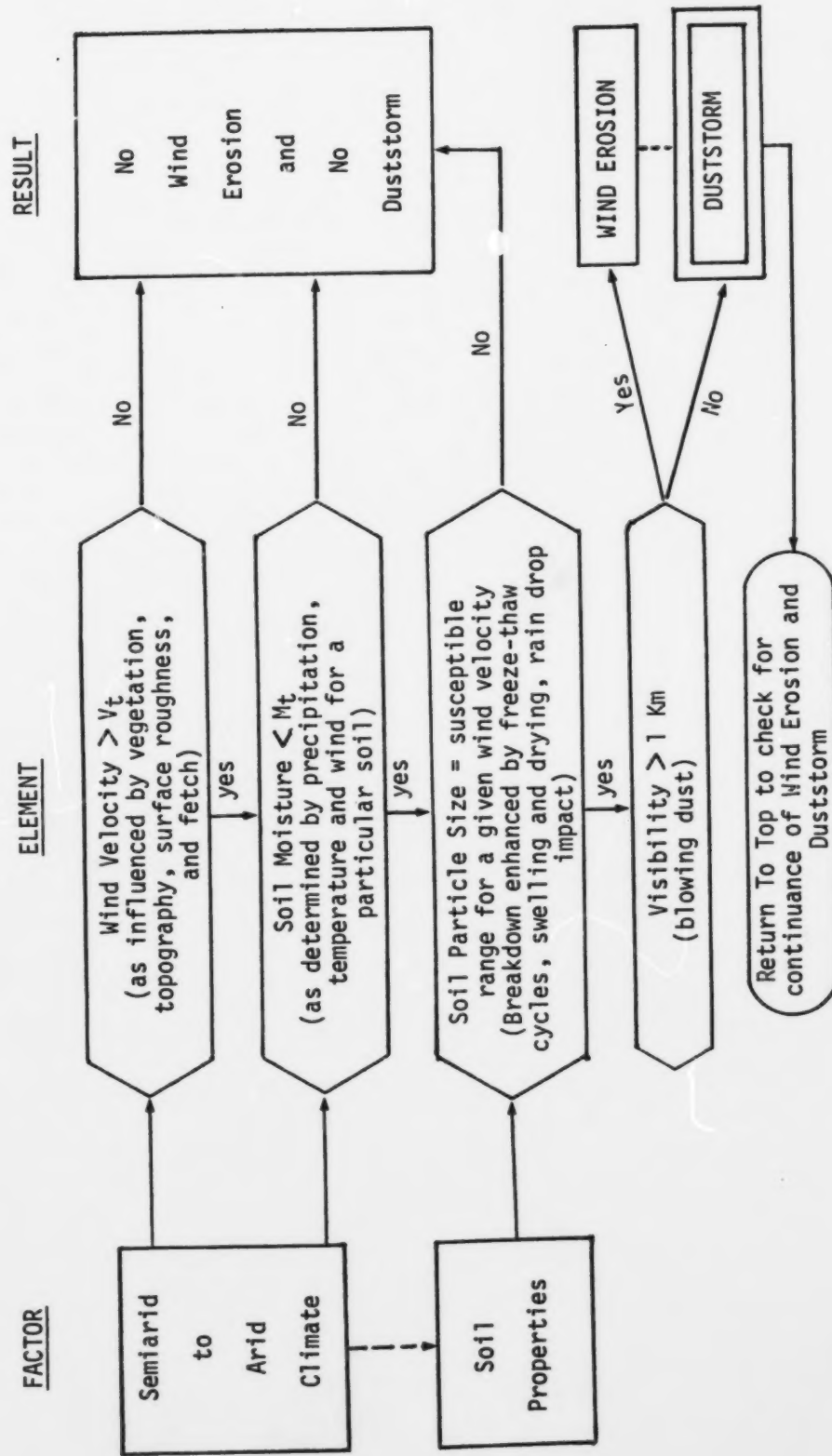


Figure 1. Dust Storm - Wind Erosion Process, a Flow Diagram.

where V_t = threshold wind velocities
 M_t = threshold cohesive force of moisture

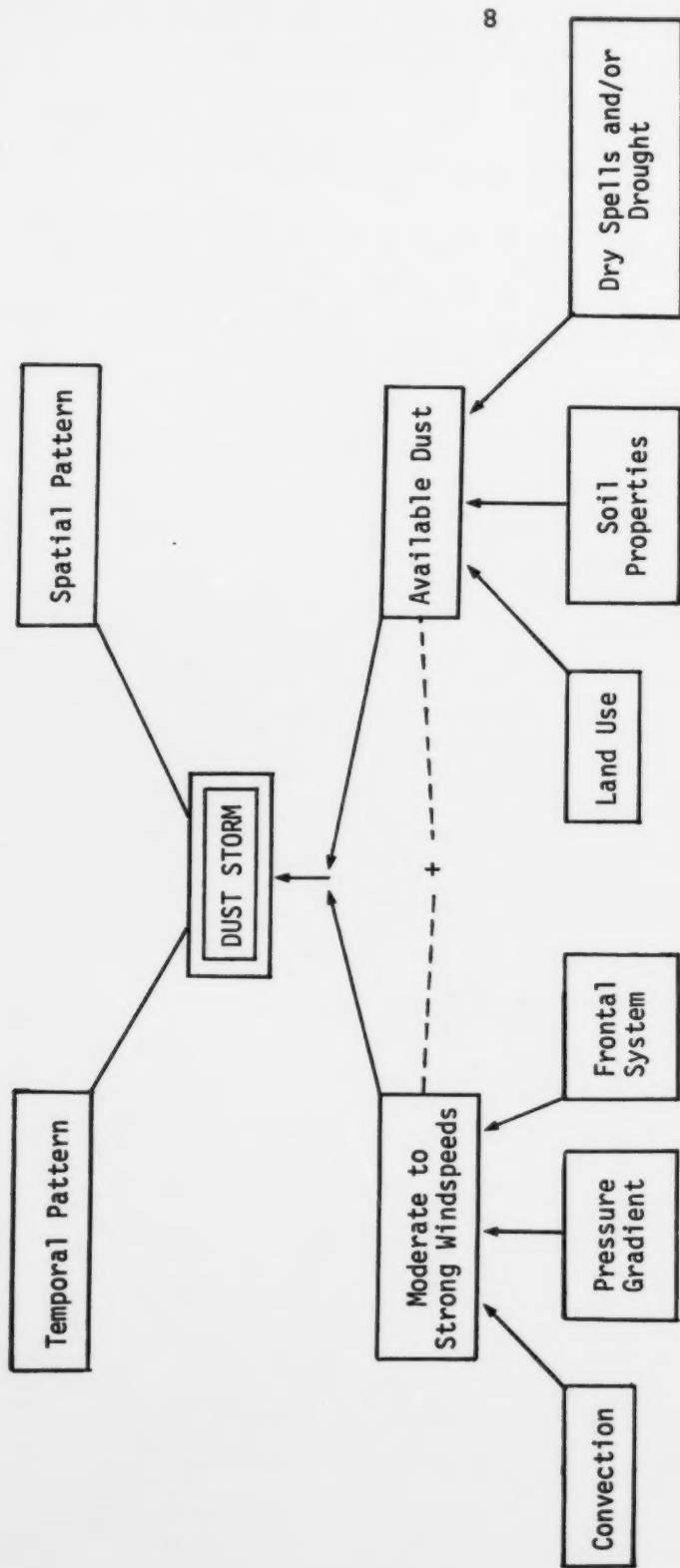


Figure 2. A Basic Model of the Dust Storm - Soil Erosion Process.

Source: A.K. Chakravarti, personal communication, April, 1985.

dust yields.

Climate has both direct and indirect effects on dust storms. An example of the indirect effect is the climatic influence on vegetation and soil properties. Vegetative growth is limited by the lack of precipitation during a drought. Since freeze-thaw cycles break down soil aggregates they result in more susceptible particles. Also rain-drop impacts and the alternate swelling and drying of particles can cause detachment of soil particles, thus rendering them more susceptible to erosion.

The climatic elements that directly affect wind erosion and thus dust storms include wind, precipitation and temperature (Figures 1 and 2). Erosion is initiated when wind speed is greater than the threshold value required to set the susceptible particles in motion. Threshold velocities vary according to the particle size and the specific gravity of dry particles (Figure 3). Continued moderate to strong winds sustain the blowing dust. Saltation, the bouncing, jumping motion of particles driven by the wind (Bagnold 1941), also acts to sustain particle movement by the force of impact of the bouncing particles. When saltation is occurring, the velocity of wind required to sustain the dust storm is less than the threshold velocity required to initiate the storm (Figure 4). Bagnold (1941) first established that the total discharge of the moving particles is a function of the cube of the wind velocity.

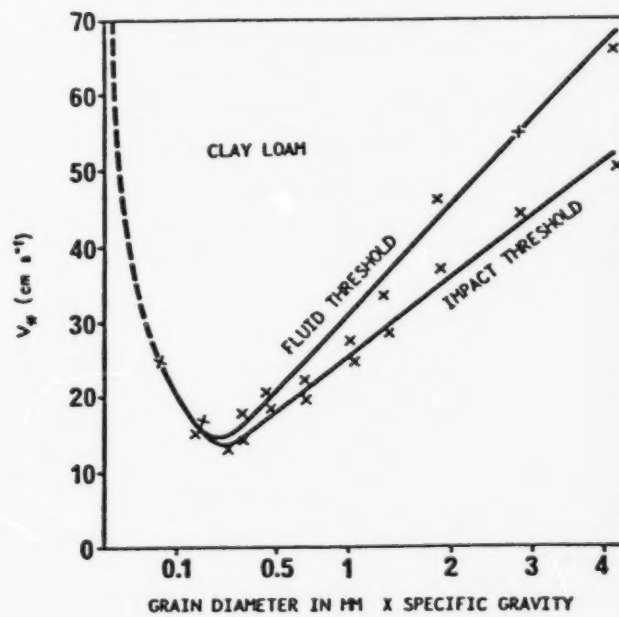


Figure 3. Variation of the Threshold Velocity with Grain Size and Specific Gravity.

Source: WMO 1983:75

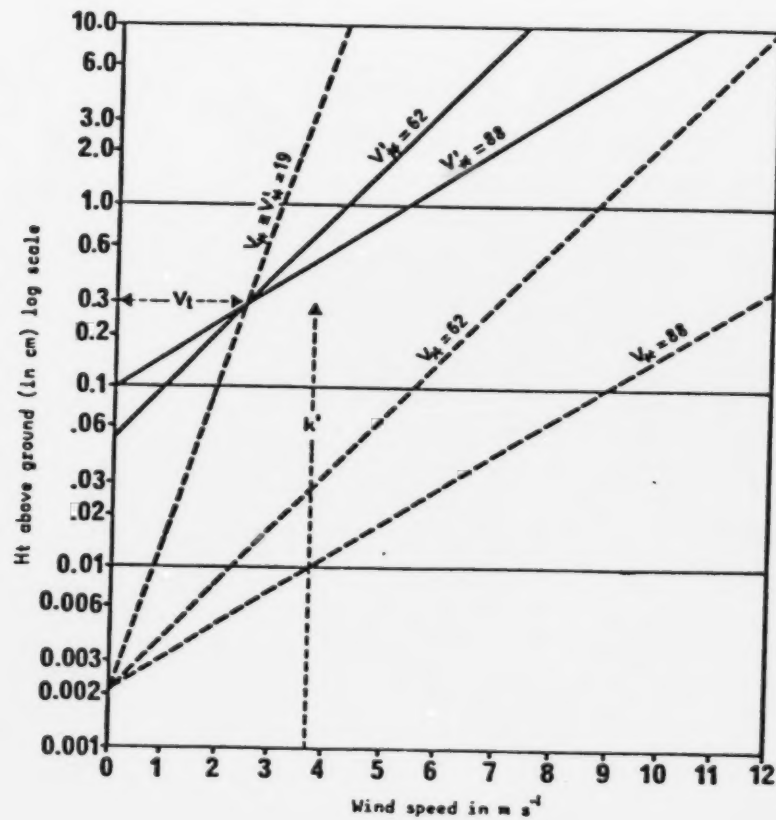


Figure 4. Wind Velocity Distributions Without (----) and With (—) Movement of Sand. V_* and V_*' in cm s⁻¹

Source: WMO 1983:76

Moisture in the soil acts to inhibit movement of the soil particles. The resisting forces of cohesion and gravity are described mathematically as being a function of the square of the equivalent soil moisture. The equivalent soil moisture is defined as the amount of water held by the soil grains divided by the amount of water held by the soil grains at a suction of 15 atmospheres (WMO 1983:91). The equivalent soil moisture is usually substituted by the more readily available Thornthwaite (1931) precipitation index (Chepil et al 1962). The moisture index developed later (Thornthwaite 1948) could also be used. The soil moisture is determined by precipitation and temperature as well as the properties of the soil.

The effectiveness of soil moisture in reducing wind erosion is questionable, however, as the upper layer of soil that is affected by wind erosion is rapidly desiccated (WMO 1983:20; Wheaton 1984:11). Brazel and Hsu (1981:302) conclude that rains from one thunderstorm are not usually an effective dust suppressor for the succeeding storm unless a surface crust forms. Therefore it can be seen that wind speed is of primary importance in the formation of dust storms if dust is available and also determines the quantity of the dust moved.

The climatic variables which affect wind erosion directly can be summarized mathematically by an index termed the climatic factor of wind erosion (Chepil et al 1962).

The climatic factor has been described by many others. The author (1984a) has applied this index to Saskatchewan and has also commented upon some of its strengths and weaknesses.

The climatic factor should be thought of as an indicator of the potential for wind erosion under ideal conditions of a bare susceptible soil, much like the concept of potential evapotranspiration. Actual wind erosion amounts can be calculated using the climatic factor in conjunction with the other factors of the wind erosion equation. The results are difficult to verify, however, due to the lack of data for actual wind erosion (de Jong 1984; PFRA 1983).

Although human activities may have increased the blowing dust hazard (Changnon 1983; Goudie 1982), semiarid areas were subjected to dust storms long before the introduction of agriculture (Pewe 1981:5). Also before settlement, prairie fires and drought acted to expose the soil to wind erosion (McCauley et al 1981:123). The semiarid area of Saskatchewan was likely not an exception. Therefore it seems that there will often be exposed soil and an availability of dust on the prairies due to climatic and anthropogenic causes. Thus other factors of dust storms other than climate are just acknowledged and are not concentrated on in this study.

1.3 Dust Storm Classifications

Even fewer classifications than definitions of dust storms can be found in the literature. Also in contrast to the definitions, all of the classifications are quite different.

Shikula (1981:263) presents four types of dust storms based on the analyses of 26 cases of dust storms in the South Ukraine of the U.S.S.R. from 1951 to 1960. These appear to be based on a combination of the timing, duration and velocities of dust storms. The categories are as follows:

- 1) storms coinciding with fixed term observations,
- 2) short term dust storms - the duration of these dust storms being between fixed time of observations,
- 3) long duration dust storms - those that last for a few days,
- 4) dust storms having wind velocities greater than the maximum threshold velocity.

Several criticisms can be made of this classification. There is no uniformity in the criteria of selecting the various types. The linkage of dust storm timing and the time of observations is artificial and may be coincidental. Also little other information is provided such as origin of the storm.

Another dust storm classification is provided by Anderson (1985) as follows:

- 1) the whirlwind type,
- 2) the wind-shift type (or the cold front type),
- 3) the windstorm type (develops in the strong pressure gradient associated with an area of high pressure.)

This is one of the better classifications in that it is based upon a uniform genetic approach. Some problems with it are that: 1) the whirlwind or dust whirl type rarely results in the visibility reduction defined to occur with a dust storm (1 km), so cannot be a dust storm. Also a whirlwind is usually not considered to be a storm. 2) Not all high pressure areas have strong pressure gradients especially in isolation from a distinct low pressure area. So the explanation should include mention of a low as the steepest pressure gradients occur between strong highs and lows. 3) The pressure gradient would have to be steep enough to produce winds of the threshold velocities.

Ostrovsky (WMO 1983) proposes three types of dust storms depending on the origin of the dust in comparison to the observation point. The types are: 1) local storms - those formed from dust particles from a local substratum raised by the wind into the lower layers of the atmosphere, 2) transit storms - those formed from dust lifted into the atmosphere outside the limits of the observation and 3) mixed storms - those resulting from a combination of transit and local dust particles.

This classification is very restrictive, however, as it

provides information only about the range of the dust from its area of origin. Another problem with it is that the classification is very fixed to a reference observational point. This means that a dust storm could be a local type and then transform into the transit type only because it moved into another observational area. This classification is realistic in terms of the third type, however, as different storm types may occur at the same time.

The genetic type of classification as set forward by Anderson (1985) may be one of the best classifications. Reasons for its superiority are that 1) it provides a uniformity of reasons for the classification, 2) it provides much information, for instance, it indicates a cause for the storm and is also indicative of such characteristics as the weather, expected life cycle, timing and area of the storm, 3) it is based on clearer differences in several characteristics of the dust storm, not just the timing or origin of the soil particles, for examples, and 4) if the weather type of a dust storm is predicted and a susceptible soil surface exists, then the likelihood of a dust storm is high. Thus this classification could be used to enhance dust storm prediction capability. Considering the importance of all its advantages, this type of classification is the one to be further developed for the purposes of this study.

One problem with the genetic approach to dust storm classification is that synoptic situations which produce

dust storms in one climate may not exist in another climate. This problem is dealt with by stipulating a climatic type in association with the classification.

The synoptic and meteorological conditions associated with dust storms have been commented upon by many authors (Anderson 1985; WMO 1983; Greeley et al 1981; Changnon 1983; Garratt 1984; Lourensz and Abe 1983; Hagen and Woodruff 1973; Martin 1939; LaDochy and Annett 1982; Morales 1979, many authors in Pewe 1981 as follows: McCauley et al; Sheng et al; Shao-jin et al; Pewe et al; Shikula, Brazel and Hsu; Wilshire et al; and Burritt and Hyers.) Yet only Anderson (1985) and LaDochy and Annett (1982) have examined dust storms on the prairies and then only very briefly. Also most of these studies concentrated on only a few dust storms, often only one storm. A study of their findings, however, should provide useful information about dust storms and should be useful in developing a genetic dust storm classification.

The studies which focus on the Great Plains of the United States, the U.S.S.R. and perhaps China would be the most appropriate as the studies of dust storms in Australia, North Africa, China and Mars, for examples, occur in different climates and weather conditions. Thus the appropriate relevant studies are indeed few. The basic physics of wind-blown material, however, is considered to be essentially the same even on another planet (Greeley et al 1981:107).

Anderson (1985) briefly discusses the visibilities and winds of a case study of his third type of dust storm, the windstorm type. He also reports the effects of nocturnal inversions as dampening the dust storm and the convection of afternoon heating as a strengthening factor. Thus there may be a diurnal growth and decay superimposed upon this type of dust storm.

Pewe et al (1981) report that most of the Arizonan dust storms are caused by downdrafts from decaying stages of large thunderstorms. Burritt and Hyers (1981) and Brazel and Hsu (1981) also find that mesoscale dust storms in Arizona are spawned by the wind shifts and winds associated with the cool air down drafts from summer thunderstorms. The thunderstorms are triggered by surface heating and/or by orographic lifting. Shikula studied dust storms in the South Ukraine, U.S.S.R. and found that the spreading thunderstorm downdraft causes some dust storms. Brazel and Hsu (1981) say that winter dust storms in Arizona are caused by frontal systems, especially dry cold fronts.

Wilshire et al (1981) discuss some of the synoptic conditions associated with a 1977 Californian dust storm. This storm was caused by the strong winds in a steep pressure gradient. The gradient resulting from the juxtaposition of a major (103.6 kpa) ridge centered over Idaho and a deep low (99.6 kpa) over the Pacific Ocean about 1400 km west of California. An unusually large and severe dust storm on the

Great Plains was examined by McCauley et al (1981:125). They found that the storm was caused by strong north-west winds associated with a storm moving into the plains. The storm moved into the area with the breakdown of the high pressure ridge that had caused the previous drought.

In China, Sheng et al (1981) have found that the two principal factors that first resulted in the dust storm that they studied were the development of the Mongolian cyclone and the downward transport of momentum of the upper westerlies.

These studies either examined the synoptic conditions of only a few dust storms, often only one, or only cursorily mentioned the synoptic situation of some of the many dust storms studied. They do, however, provide some indication of some genetic types of dust storms. Therefore the following genetic dust storm classification for continental temperate climates is proposed:

- 1) convective dust storm (air mass)
- 2) frontal dust storm (wind shift)
- 3) pressure gradient dust storm (wind storm)
- 4) mixed type dust storm

Alternative names are given in brackets. Confirmation for this classification for the Prairies has not yet been established, but is an objective of further study. A brief description of each type based on the combination of findings in the literature and the author's experience follows.

The convective dust storm is the type which is triggered by the convective winds of surface heating. Surface heating in a fairly homogeneous air mass produces a steepened lapse rate and greater atmospheric buoyancy. This type has a distinct diurnal periodicity with a maximum frequency in the afternoon and a minimum frequency just before sunrise. Also the convective dust storm would be quite seasonal, being restricted to the summer months with occasional occurrences in the spring and fall.

Frontal dust storms are those that are triggered by the advancement of a frontal system. Cold fronts are more likely to induce dust storms as these fronts have stronger winds than the warm, occluded or stationary front. A cold front associated with moist and unstable air masses may produce more frequent and more severe dust storms than the dry cold front depending on the wind speeds associated with the fronts. Although the rain may wash out some of the dust, raindrop impact will tend to detach more particles. Also the downdraft associated with a thunderstorm of the wet cold front may intensify the dust storms as dust storms are known to be associated with thunderstorms (Burritt and Hyers 1981; Brazel and Hsu 1981, for examples). Dust storms may be associated with warm fronts, especially if the warm air is unstable and thunderstorms result.

The third dust storm classification is the pressure gradient type. These are the dust storms which are a result

of the strong winds associated with the steep surface pressure gradient between low pressure and high pressure areas. The pressure gradient is steep enough to produce winds that are greater or equal to the threshold velocities of the soil particles. The dust storms formed with the strong outpouring of air in these transition areas are the ones that can occur at any time of day and can have the longest durations of all the types except for the mixed type. With this latter storm one type may be dying out as another replaces it.

Two or more of these dust storm types may occur simultaneously and thus be more appropriately termed the mixed type of dust storm. For instance, the convective type could be triggered by a frontal system or they may follow one another so closely in time that they merge with one another. A cold front may set off a dust storm which is sustained by the pressure gradient. This pressure gradient is set up between the receding low and the advancing high pressure system. So the last type in the classification acknowledges these situations and thus is labelled the mixed dust storm.

In summary, a dust storm classification has been devised based on the strengths and weaknesses of the existing classifications, discussions of the synoptic conditions of dust storms and the past observations of the author. These classifications of the synoptic conditions of dust storms have been used to describe dust storms of other locations. This is why it is necessary to substantiate and possibly

revise the categorization based upon analyses of dust storms of Saskatchewan and the Prairies.

1.4 Impacts of Dust Storms on Agriculture and the Significance of the Study

An examination of the effects of dust storms on both the physical and social environment reveals that the impacts are numerous and can be particularly severe (Pewe 1981; Wheaton 1985). A study of the effects of dust storms on agriculture, particularly wind erosion of soil, is undertaken in this study. An application of a knowledge of dust storms to agriculture is significant as agriculture is an important component of the province's economy. The significance of the study can also be viewed in terms of an increased knowledge of a climatic phenomenon.

The spatial pattern of wind erosion risk due to climate as based on the wind erosion climatic factor exhibits a considerable variation in Saskatchewan (Figure 5). The spatial pattern of dust storms will be determined and compared to that of wind erosion risk. Theoretically, they should be very similar. There is no information on dust storm patterns of which the author is aware. A comparison of dust storms and wind erosion risk would be useful in assessing the impact of dust storms on agriculture.

Significant amounts of soil can be lost by wind erosion during dust storms. The annual soil loss from cultivated land in the Prairie Provinces due to wind erosion is conser-

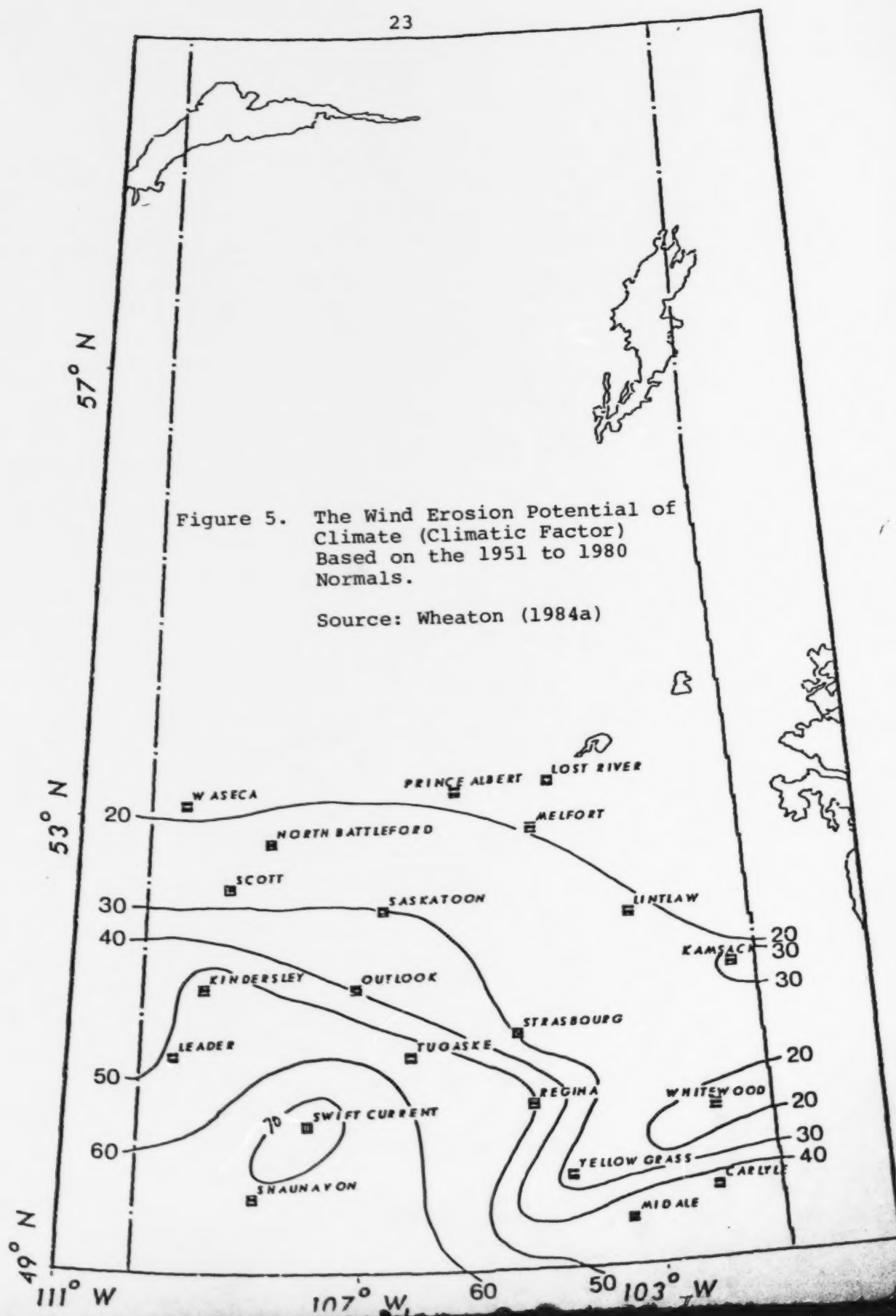


Figure 5. The Wind Erosion Potential of Climate (Climatic Factor) Based on the 1951 to 1980 Normals.

Source: Wheaton (1984a)

vatively estimated to be 160 million tonnes. Nearly 58% of the total annual soil loss due to wind and water erosion on the prairies can be ascribed to wind erosion (Sparrow 1984: 111). For example, a soil layer 0.5 cm deep can be removed each hour if the wind speed as measured at a height of 10 m reaches 15 m s^{-1} and if the soil is bare and easily erodible (WMO 1983:11). Thus it is because of the importance of wind erosion to agriculture that the effect of dust storms on agriculture is being studied. Agriculture is one of the major activities of man that is affected by dust storms (Pewe 1981).

1.5 Study Area

The application of dust storms in terms of a consideration of their effect on wind erosion of soil and thus on agriculture also leads to a definition of the study area. The study area is the agricultural area of Saskatchewan (Figure 6). It is an area bounded by the provincial boundaries to the east, west and south. The northern boundary is approximated by the limit of the northern administrative area which is at about $54^{\circ}40'$ north at the intersection of the western boundary and runs across to about $53^{\circ}40'$ at the intersection of the eastern boundary (Richards and Fung 1969). The occurrence of dust storms is likely rare north of the agricultural area as inferred from the distribution of wind erosion risk (Figure 5), days with blowing dust

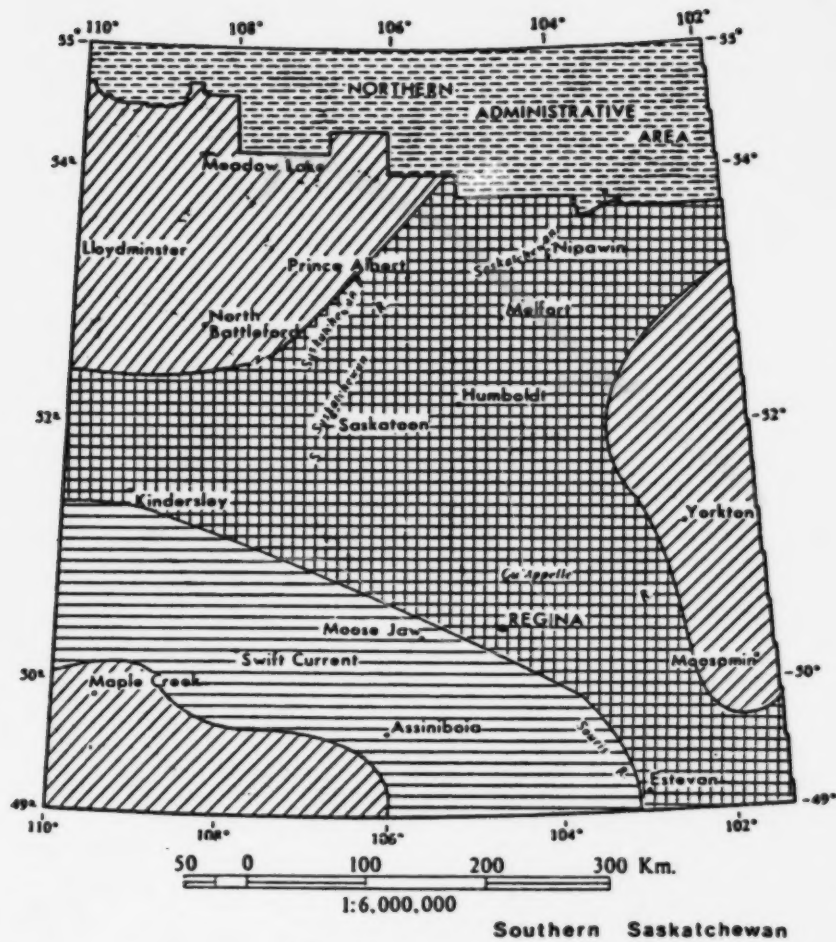


Figure 6. Study Area (South of the Northern Administrative Area) and Land Use.

Source: Richards 1981:114

(Tables 2 and 3) and because of the lower wind speeds and lack of soil in the north. Thus the study area is selected by reason of the frequency of dust storms and their effect.

Table 2. Annual Frequency of Days with Blowing Dust, 1977 to 1983.

Station	Year							1977-1983 ^a Period Mean
	1977	1978	1979	1980	1981	1982	1983	
Broadview	2	M	1	4	8	3	3	3.5
Estevan	1	2	M	6	10	M	0	3.8
Hudson Bay	2	M	M	M	1	M	M	M
Kindersley	4	1	2	1	8	8	1	3.6
Meadow Lake ^b	M	M	1	M	M	M	M	M
Moose Jaw	7	1	3	5	14	3	1	4.8
Nipawin	3	M	M	2	M	1	0	1.5 ^d
North Battleford	6	1	M	3	3	2	0	2.5
Prince Albert	4	M	M	M	2	1	1	2.0
Regina	9	1	1	0	19	2	3	5.0 ^c
Saskatoon	7	3	3	4	8	5	2	4.6
Swift Current	4	M	M	2	12	2	1	4.2
Wynyard	4	M	2	4	9	5	1	4.2
Yorkton	6	2	1	6	12	2	1	4.3
Areal Mean	4.5	1.6	1.8	3.4	8.8 ^c	3.1	1.2 ^d	

^aNote that not all of the years in this period are available.

^bNot enough data for use in the analyses.

^cMaximum value of areal mean or period mean.

^dMinimum value of areal mean or period mean.

M indicates missing value.

Source of data: Environment Canada 1977-1983.

Source: Wheaton 1984b

Table 3. Total Monthly Number of Days with Blowing Dust (D), Saskatchewan Stations^a.

	January	February	March	April	May	June	July	August	September	October	November	December
1977	0	0	14	31 ^b	10	0	0	2	0	1	1	0
1978	0	0	0	0	1	4 ^b	2	0	0	1	3	0
1979	0	0	1	0	0	5 ^b	1	1	6	0	0	0
1980	0	0	0	0	22 ^b	2	3	0	2	4	3	1
1981	0	0	0	57 ^b	40	1	3	0	4	0	0	1
1982	0	0	1	18 ^b	6	6	0	2	1	0	0	0
1983	1	0	0	0	1	3	0	3	7 ^b	0	0	0

^aThe number of stations with data ranged from seven to thirteen.^bMaximum monthly value for the year.

Source: Wheaton 1984b

2 STUDY OBJECTIVES

The following points summarize the main objectives of the study:

- 1) To determine the nature and characteristics of dust storms in terms of their associated weather, synoptic and climatic conditions.
- 2) To provide a draft definition and classification of dust storms based upon the findings of the first three objectives.
- 3) To attempt to model dust storms, mainly by conceptual means in order to improve understanding of the process.
- 4) To assess the impacts of dust storms on wind erosion of soil.
- 5) To explore the diurnal and seasonal rhythms of dust storms and wind erosion risk in order to assess their relationships as well as their temporal changes. Year to year and season to season dust storm trends are examined.
- 6) To delineate the spatial patterns of dust storms and to classify the regions of different dust storm frequencies. The spatial pattern of dust storms will be compared to that of wind erosion risk. An examination of the dimensions of dust storms would be useful.

Points one through four have already been considered in the introduction. A consideration of data and its availability, procedures, and the temporal and spatial characteristics of dust storms follow.

3 NATURE AND AVAILABILITY OF DATA AND PROCEDURE

3.1 Nature and Availability of Data

Visibility data, that is hourly visibility amounts and records of days with blowing dust, are the key indicators of whether or not a dust storm has occurred at a location. The network of weather stations that record visibility data (Figure 10) consists of 12 stations of fairly good distribution across the study area. Several stations outside of the study area should also be used to improve the assessment of boundary conditions. Visibility data has been published in terms of the number of days with blowing dust since 1977 for most of these stations (Environment Canada 1977 to 1984). This data could be supplemented by the observer's remarks made in the monthly Climatological Station Registers.

The other meteorological elements for which daily and hourly data are required are mainly wind speed, wind direction, temperature, precipitation and possibly humidity pressure and evaporation. These data will be required for the days with dust storm and possibly for a few days before the dust storm to provide information about antecedent conditions. Stations that observe wind are unfortunately not as common as those observing just temperature and precipitation. Only 21 stations recorded wind data during the 1951 to 1980 period and even fewer records are available for previous periods (Figure 7).

Other information that should be examined include soil

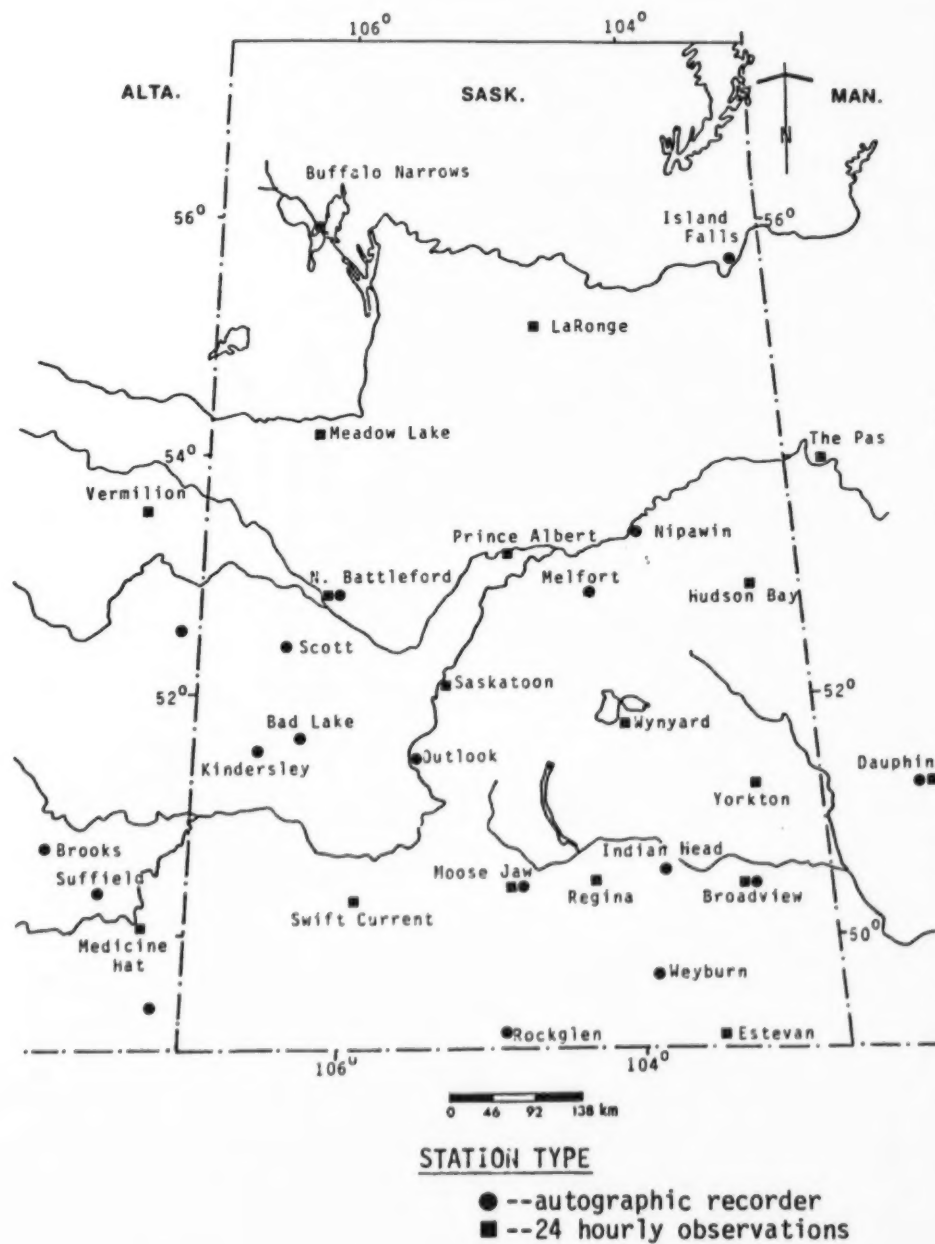


Figure 7. Recording Wind Network.

Source: Environment Canada (AES) 1981

moisture, dust fall, land use, weather station site descriptions and satellite imagery. Soil moisture data as calculated using a modified Thornthwaite method are available from Environment Canada (P. Louie, personal communication). Dustfall data have been collected at several locations by Saskatchewan Environment for at least five years (L. Lechner, personal communication). Land use information is available from various publications, including the Atlas of Saskatchewan (Richards and Fung 1969). A weather station site description is provided with the wind normals (Environment Canada 1982). Satellite imagery can be obtained from the Prince Albert Satellite Station or from other locations in Canada and the United States if it is not available from Prince Albert.

Climatic data that are needed are monthly means, extremes, and totals and normals for each of the weather elements previously mentioned. The data are available for most of the weather elements for all of the study area stations for at least 30 years of record (Environment Canada 1951 to 1984).

Surface synoptic weather maps for the days or times with dust storms are also required. Some are occasionally out of print so their availability may be sporadic. The synoptic maps are available from such locations as the United States Department of Commerce (NOAA) and the National Weather Service.

3.2 Recommended Procedures

The first step is to identify the dust storms which have occurred in Saskatchewan. This can be done by means of the weather data, especially visibility and wind speed, the observers' remarks and the available synoptic maps. To provide the climatic setting of the study area, a climatic summary of the stations should be tabulated, including site descriptions.

Annual and seasonal dust storm totals should be compiled so that temporal variations as well as trends can be studied. Frequency distributions in the form of histograms would aid in the visual interpretation of these data. Various means are used to evaluate trends and a couple of methods will be used for comparison purposes.

A climatic summary for the study area stations, including site descriptions should be provided in order to establish the normal climatic conditions of the area. The normal wind erosion climatic factor should also be included.

The relationship of dust storms and weather elements should be explored initially by means of a table summarizing the weather elements during dust storms. This would help to characterize dust storms in terms of their attendant weather conditions. Then more advanced statistical analyses such as principal component (harmonic) analysis and/or discriminant analysis can be applied. These procedures should provide such information as which elements have the strongest asso-

ciation with dust storms. The frequencies of the main types of synoptic conditions found in association with dust storms should also be tabulated and their distribution studied. This information could be used to assess the extensiveness of dust storms as well as to substantiate or redirect the dust storm definition and classification. Also there would likely be areas in which dust storms are expected to occur but for which visibility and wind data are not available. Dust storm risk could be estimated based on the interpretation of existing wind data and the analysis of patterns of the isobars. The presence of dust storms could possibly be confirmed using satellite imagery if the storm did not occur before the satellites were being used.

Case studies of a few individual dust storms through space and time should be undertaken to substantiate the study of dust storms. They would be used along with the other information, to refine the definition and classification of dust storms. They also aid in improving the knowledge of the duration and life cycle of dust storms in Saskatchewan and the Prairies.

Satellite imagery of some of the case studies of dust storms should help to explore their intensities and areal distributions. Other studies (e.g. in Pewe 1981 and Anderson 1985) have shown that satellite imagery can be used to study the coverage, source, intensity and the life cycle of dust storms.

The foregoing analyses could be used to delineate the temporal and spatial patterns of dust storms. These patterns should be analyzed including comparisons with the patterns of wind erosion. The temporal and spatial patterns of dust storms and wind erosion should be compared to those of dry spells and droughts to assess their level of association.

The results of all of the analyses could be used to develop and to refine a dust storm model. The wind erosion model also needs further development (Wheaton 1984b) and these could be developed in conjunction with one another. The wind erosion-dust storm model is presented in many forms. Conceptual information (Figure 2) and process flow structures (Figure 1) as well as a mathematical model could be further developed. The mathematical model should be subjected to sensitivity analyses to determine how much change in each factor, with the others held constant, results in what change in dust storms.

4 CASE STUDIES OF DUST STORMS - THE HISTORICAL AND
 RECENT BACKGROUND

McCauley et al (1981) provides a brief account of the dust storms throughout historical times on the Western Great Plains of the United States, but there are likely fewer accounts of the earlier dust storms for the Canadian Prairies. The only information besides the newspapers, the author is aware of is Gray (1978). Gray (1978) dwells only on the dust storms of the 1930's. McCauley et al (1981) reports that the following years after the 'dirty thirties' were also severe dust storm years; the 1950's and mid 1970's. Lockertz (1978), as referenced by McCauley et al (1981), states that more land in the Great Plains was damaged annually by wind erosion during the 1950's than during the 1930's, although the earlier dust storms were more spectacular. Also soil loss due to wind erosion in the mid 1970's was comparable to that of the 1930's. The same recurrence of wind erosion and dust storms may have happened on the prairies.

Dust storms to be studied as case studies should be at least one that occurred during the 1930's, one of the drought year of 1961 and one of a more recent drought of partially drought year such as 1981 or 1984. The study of selected cases of dust storms will facilitate the characterization of dust storms.

5 TEMPORAL CHARACTERISTICS OF DUST STORMS

Wind erosion has pronounced diurnal, seasonal and year to year rhythms, so it follows logically that dust storms should have distinct temporal rhythms. Annual and monthly frequencies have been tabulated and certainly do show wide swings in time (Wheaton 1985, Tables 2 and 3). The frequencies in these tables were based on the records of numbers of days with blowing dust (Environment Canada 1977-1983). As stated in the introduction to this study, a day with blowing dust is considered to be the same as a day with a dust storm. Thus Tables 2 and 3 can be considered to be the annual and monthly frequencies of dust storms. The distribution of the areal mean annual frequency of dust storms and the mean monthly frequency of dust storms have been graphed based on these data (Figures 8 and 9).

Most of the thirteen stations with available data have at least one dust storm annually and one station had as many as 19 dust storms in one year (Table 2). The mean annual value for the seven year period of record shows that, on average, wind erosion and dust storms occur at least once and often three to four times annually in agricultural Saskatchewan. This frequency represents the movement of large quantities of soil.

The distribution of the areal mean annual number of days with dust storms exhibits a cyclical appearance (Figure 8). The areal mean annual number of dust storms was calcu-

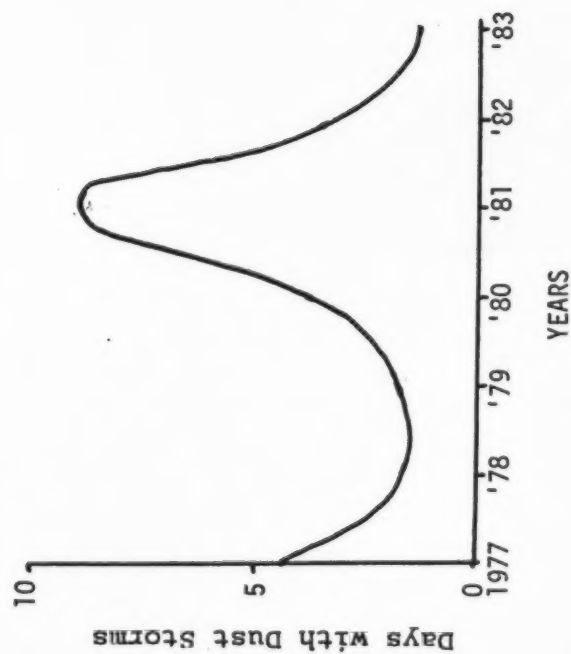


Figure 8. Areal Mean Annual Frequency of Days with Dust Storms (1977-1983), Saskatchewan.

NOTE: The number of stations ranged from seven to thirteen.
The range of annual values is from 1 to 19.

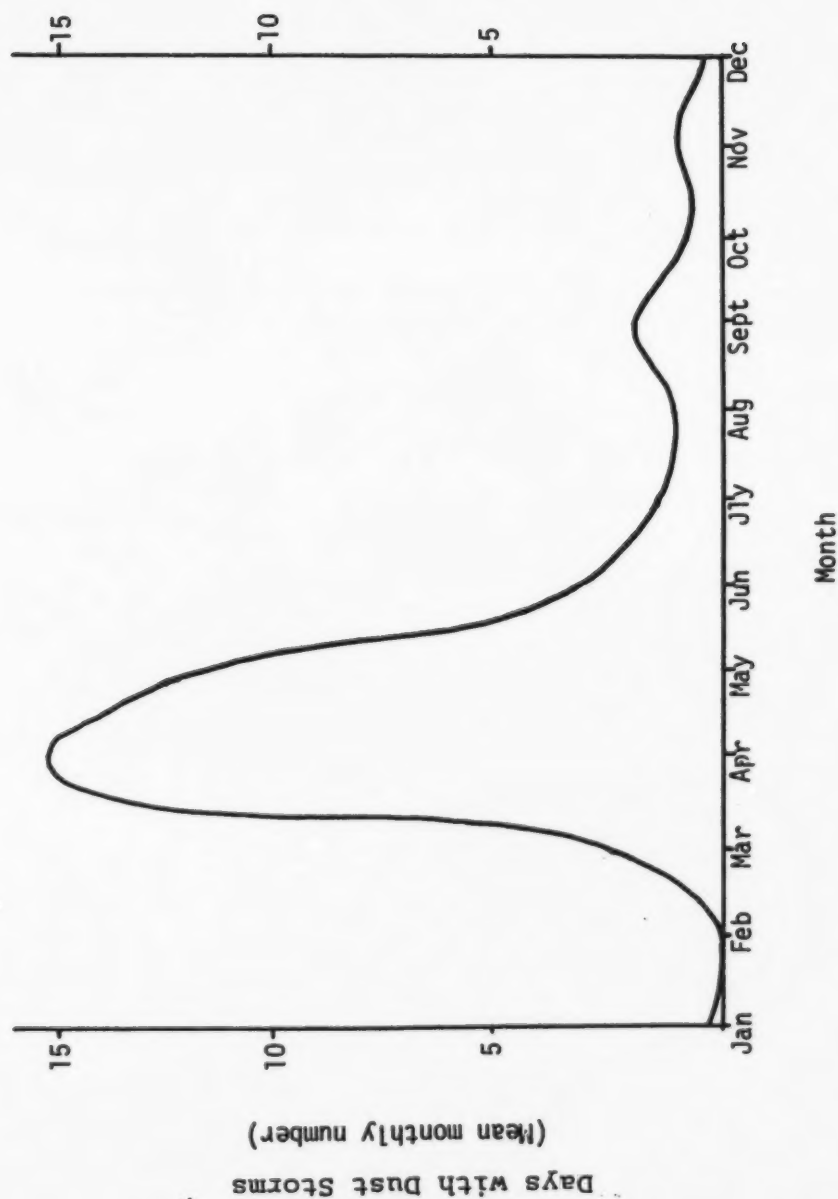


Figure 9. Distribution of the Mean Monthly Frequency of Dust Storms (1977-1983), Saskatchewan.

NOTE: The number of stations ranged from seven to thirteen. The total monthly number of days with blowing dust ranged from 0 to 57.

lated by summing the annual totals for all stations (thus areal) and dividing the number of stations as follows:

$$y = \frac{\sum_{i=1}^n Da_i}{n}$$

where: y = areal mean annual number of dust storms
 i = the station number
 n = the number of stations
 Da_i = the annual total of dust storms at station i

There is a primary peak in 1981 and a secondary peak in 1977. The most recent drought year, 1984, will likely show a peak as well. A primary trough occurred in 1983 and a close secondary trough in 1978.

The problem of short record length is epitomized by this graph as only a short portion of the cyclical variation can be seen. Means of extrapolating these curves backwards (and forwards) using the knowledge of the association of wind erosion, dust storms and climate, such as drought, and dry spells, should be developed. It has been shown that a wind erosion model resulting in the climatic factor follows the same general trends as the annual dust storm frequency (Wheaton 1984b). Improvements upon such models to extrapolate dust storm days backwards in time would have to be made. Other unpublished data, such as the Climatological Station Records, may also have useful information. Also, as mentioned previously, existing wind and isobaric information can be used to complete the picture of the wind field. This

information used in conjunction with climate and land use could be used to model the occurrence of dust storms.

The monthly frequency of dust storms reveals a definite seasonal pattern (Table 3, Figure 9). The mean monthly frequency of dust storms was calculated using the following equation:

$$y = \frac{\sum_{i=1}^n Dm_i}{n}$$

where: y = the mean monthly frequency of dust storms
 i = the year number in the period of record, where the first year is numbered 1
 n = the number of years of monthly records. For example, if there are seven complete Januaries, $n=7$
 Dm_i = the total number of days in a month with dust storms in year i

The primary peak of dust storm frequency generally occurs in the spring for most years. Only one year, 1983, had a peak in the fall. Some of the main reasons for this seasonality are the high wind speeds at this time of the year, the sparse vegetation cover, the low precipitation amounts and soil moisture (Wheaton 1984b). The distribution of mean monthly dust storm frequencies has a pronounced peak in April, a weak secondary peak in September and very low to nonexistent amounts in the winter months.

The short record length, that is only seven years, is also a problem for a more stable assessment of seasonality.

The diurnal characteristics of dust storms should undergo further examination and they have been mentioned in

the introduction. Nickling and Brazel (1984) found that some stations had clear modes for afternoon storms, while other stations had many dust storms occurring during the night and the morning hours. The former timing is indicative of the convection type of dust storm and the latter is indicative of the frontal and pressure gradient classifications developed in this study.

6 SPATIAL CHARACTERISTICS OF WIND EROSION AND DUST STORMS

The spatial characteristics of dust storms are the least examined features of the dust storm. Even Nickling and Brazel (1984) pay only passing attention to the spatial pattern even though the phrase "spatial characteristics of dust storms" is in the title of the paper. Chepil et al (1962) mapped the wind erosion climatic factor for the Great Plains and a portion of the Canadian Prairies. Wheaton (1984) mapped the wind erosion climatic factor on a much larger, more detailed scale for Saskatchewan with much more recent climatic data (Figure 5). The spatial patterns of dust storms have not previously been mapped, to the authors' knowledge, for any location in North America and perhaps elsewhere. Therefore, this paper includes the first of such maps (Figure 10).

The map of the spatial pattern of dust storms was drawn based on data from Table 2 and knowledge of the areal pattern of wind erosion risk, primarily. The central area of the dust storm map has the greatest mean annual number of dust storms numbering four to over five per year. This area is in the shape of an ellipse reaching northward past Saskatoon and southward past Regina and probably on into the Great Plains of the United States. Regina is the station with the greatest mean annual number of dust storms, with an extreme maximum of 19 in 1981. The area with the lowest frequency of dust storms is in the northeast, as expected,

DUST STORM FREQUENCY RATING:

< 3 - low
 3-3.9 - intermediate
 4-4.9 - high
 ≥ 5 - very high

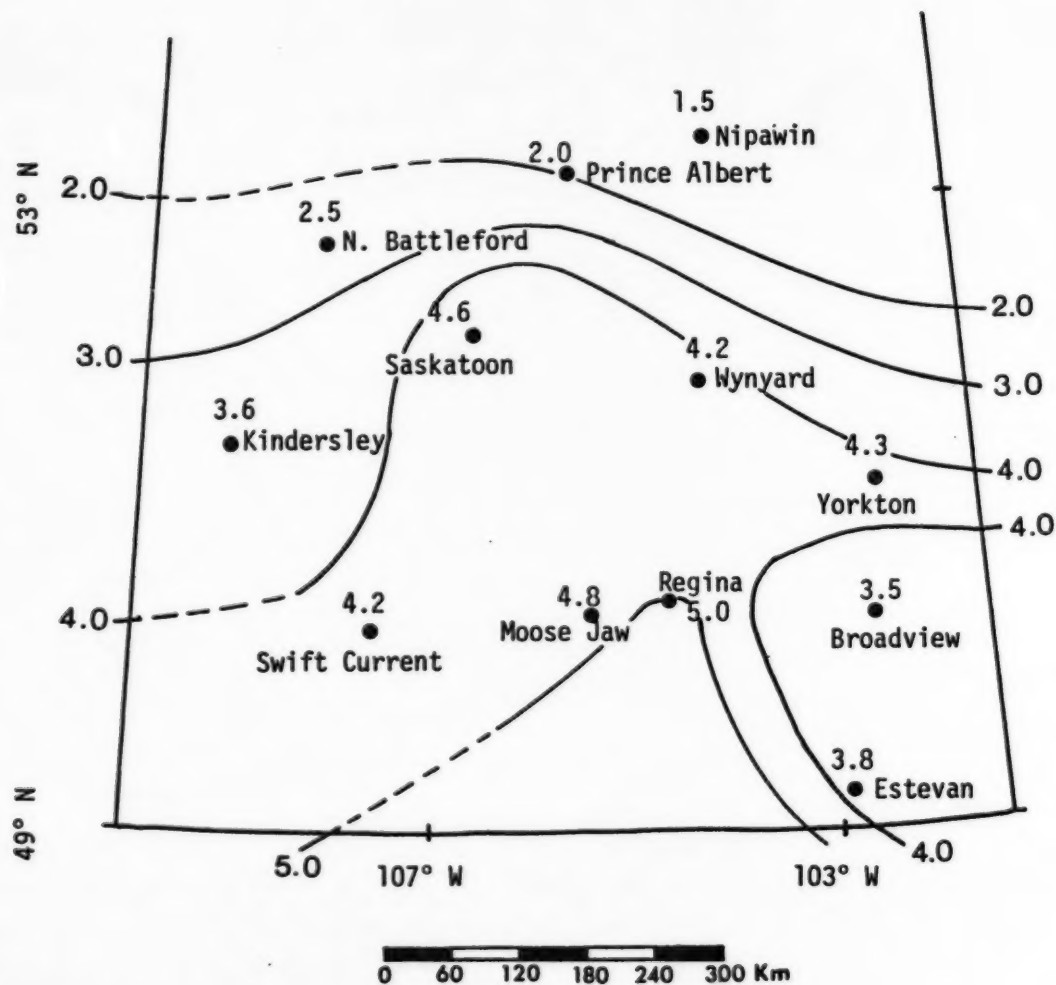


Figure 10. Mean Annual Dust Storm Frequency, Agricultural Saskatchewan (1977-1983).

Note: Lines are dashed where information is insufficient.

as this pattern corresponds closely with that of the lowest risk of the wind erosion map.

The wind erosion risk and dust storm frequency maps do show an unexpected departure from one another in the southeast and especially the southwest. The dust storm frequency is quite high in the southeast as compared to the wind erosion risk map. The core of maximum wind erosion risk is in the southwest, whereas the dust storm frequencies are only at a secondary peak in the southwest. This latter discrepancy could be due to a lack of information regarding dust storm frequencies in the southwest and/or to the land use of the southwest being primarily rangeland.

The dashed dust storm isolines indicate that there are several areas of uncertainty on the map due to lack of data. This problem could be alleviated by the inclusion of several stations from outside of the study area as well as by techniques to be developed to estimate dust storm frequencies. Satellite imagery should be useful in filling the void of spatial uncertainty, especially in recent years. The most serious deficiencies of data exist for the southwest and central portions of the study area. This is highly unfortunate as these are the areas of high to very high dust storm frequency.

In summary, the northern agricultural portion of the study area, especially the northeast, is of low dust storm risk, the southeast and central southwest are of intermedi-

ate risk and the central to central south are of high to very high risk. The discrepancies of the dust storm and wind erosion risk maps are interesting and it will be useful to resolve them.

The areal pattern of mean monthly dust storm frequencies and that of years with many dust storms, for example, should prove just as informative and thought provoking or even more so than the mean annual frequencies. These should be examined in further studies.

7 SUMMARY AND CONCLUSIONS

A more useful definition of dust storms and a more meaningful and informative classification of dust storms have been developed herein. Preliminary graphical models of the wind erosion process in combination with the dust storm process have been conceptualized. Further discussion of these will help to clarify understanding of these complex processes and their interrelationships.

Several other important 'firsts' characterize this study. This paper represents the first attempt to present the quantitative temporal distribution of dust storms for any province in Canada. It is the first attempt to map the spatial distribution of dust storms for any area, to the author's knowledge.

8 RECOMMENDATIONS

This study provides only a preliminary examination of the climatic assessment of dust storms. Many specific suggestions for improvement are given in the study and some general approaches are as follows:

- 1) to further assess the nature and characteristics of dust storms in terms of their associated weather, synoptic and climatic conditions.

- 2) to refine and substantiate the draft definition and classification of dust storms based upon increased knowledge of the phenomenon.

- 3) to determine the frequency of occurrences of dust storms and explore the trend of such frequencies. The nature of future dust storms could also be estimated as based on climatic data from a global circulation model(s). Thus both past and future trends could be examined.

Much more is generally known about wind erosion than dust storms, although there is still much to be learned about wind erosion. So this existing knowledge should be refined and further developed to serve as a foundation to build further knowledge of dust storms.

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